LCA Methodology

A Consistent Framework for Assessing the Impacts from Resource Use
A focus on resource functionality

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Abstract

Background. The quantification of resource depletion in Life Cycle Assessment has been the topic of much debate; to date no definitive approach for quantifying effects in this impact category has been developed. In this paper we argue that the main reason for this extensive debate is because all methods for quantifying resource depletion impacts have focussed on resource extraction.

Aim and Scope. To further the state of the debate we present a general framework for assessing the impacts of resource use across the entire suite of biotic and abiotic resources. The main aim of this framework is to define the necessary and sufficient set of information required to quantify the effects of resources use.

Methodology. Our method is based on a generic concept of the quality state of resource inputs and outputs to and from a production system. Using this approach we show that it is not the extraction of materials which is of concern, but rather the dissipative use and disposal of materials. Using this as a point of departure we develop and define two key variables for use in the modelling of impacts of resource use, namely the *ultimate quality* limit, which is related to the functionality of the material, and *backup technology*. Existing methodologies for determining the effects of resource depletion are discussed in the context of this framework.

Results. We demonstrate the ability of the general framework to describe impacts related to all resource categories: metallic and non-metallic minerals, energy minerals, water, soil, and biotic resources (wild or domesticated plants and animals).

Recommendations focus on suggestions for a functionality measure for each of these categories; and how best the two modelling variables derived can be determined.

Keywords: Abiotic resource depletion; biotic resource depletion; life cycle impact assessment; resource use

1 Background

Impacts from resource use (often named 'resource depletion'[1]) has been a prominent impact category in most environmental impact assessment methods for Life Cycle Assessment (LCA) developed since the early 1990s. In accordance with the general concerns of the broader public at the time, emphasis has been on abiotic resources, specifically on energy and metallic minerals, and on the extraction stage of the minerals life cycle.

The numerous methodologies proposed for the impact assessment of resource use were reviewed by the SETAC Working Group IA-2 (Lindeijer et al. 2002). Based on a suggestion of Finnveden (1996), the methodologies were categorised into four main approaches (**Table 1**).

Type 1 and 2 methodologies focus on current consumption (for type 2 in relation to perceived abundance or scarcity), while type 3 and 4 focus on future consequences.

Resources are entities valued for the functionality that they deliver to human society. The major deficiency in Type 1 and 2 methodologies has been their lacking ability to adequately reflect the loss in functionality related to their use.

Another problem with Type 1 and Type 2 methodologies has been their emphasis on resource extraction as opposed to an emphasis on product use and disposal, as the human activity responsible for resource depletion. Concern has been raised, e.g. in MMSD (2001), that neither size of deposits

[1] As noted by several authors, e.g. Ayres et al. (2001 and 2003), metals cannot be depleted, they can only be dissipated. Thus, the popular name of 'resource depletion' for this impact category, is actually a misnomer in the context of metals utilisation.

Table 1: Synthesis of methodologies for assessing impacts resource use (after Lindeijr et al. 2002)

Characterisation Type	Assessment Method
Type 1	Summation of energy and materials on energy and mass basis, relative to mass of metals produced, not nature of ore body
Type 2	Aggregation (Q) according to measure of reserve deposits (D) and current consumption (U)
	2a: $Q = 1/D$ (Fava et al. 1993)
	2b: $Q = U/D$ (Guinée and Heijungs 1995)
	2c: $Q = 1/D*U/D$ (Heijungs et al. 1992, Guinée and Heijungs 1995, Mueller-Wenk 1978)
Type 3	Aggregation of energy impacts based on future scenarios, e.g., impacts associated with recovery to initial state (Pedersen Weidema 1991, Steen and Ryding 1992)
Type 4	Aggregation of exergy and/or entropy impacts, e.g., Finnveden (1996) proposes an exergy approach

nor current consumption has any relation to the damage from using a given resource. Resources are not depleted through mining, they are depleted only when they leave the industrial economy in such a form that the functionality for which they are desired can no longer be restored to them. For example, if a resource is deposited in a form that allows later reuse, i.e. if it is not dissipated, its current use may not involve any additional impacts. And if a scarce resource has an obvious substitute, its dissipation may be less damaging in terms of resource consumption than the dissipation of an abundant resource without available substitutes.

A further problem with Type 2 methodologies is that available reserve deposits are defined in the context of economic availability; this incorporates considerations of the technologies available to exploit them, their accessibility (both geographically and politically), etc. As technologies advance and are better able to process ores of lower grades the reserve base grows. Known reserves are not static, and this introduces a significant element of arbitrariness in Type 2 methodologies. Consideration of other work on resource economics has been included in the development of the framework presented in this paper (example references include AusIMM 2001 and JORC 1999).

Type 4 methodologies involve some conceptual problems, since entropy and exergy are very abstract indicators for loss of functionality, which makes it questionable whether they can be generally accepted as representative for the very specific situations that apply to each type of resource. Also the definition of an entropy baseline on which to base a quantification is debatable.

In this paper we propose a framework for Type 3 methodologies based on the concept of resource functionality. The framework is consistent for all resources (biotic and abiotic) and that it takes into account the current understanding of LCA system boundary issues. Specifically the resources considered in defining this framework are:

- metallic minerals
- non-metallic minerals
- energy carriers (chemical or nuclear)
- freshwater
- fertile land
- wild and domesticated organisms

2 Presentation of the Framework

As a point of departure, we wish to consider both abiotic and biotic resources and to deliver a consistent methodology for assessing the impact of the use of these resources. *Abiotic resources* include metallic and non-metallic minerals, energy carriers, water and soil, while *biotic resources* include wild or domesticated plants and animals. These resource categories reflect the consensus position presented in the definition studies of the UNEP SETAC Life Cycle Initiative (Jolliet et al. 2003).

We define:

- **Resource extraction** as the human activity taking resources from nature and supplying it to the technosphere (e.g. the mining process where metals are taken from the

earth's crust and supplied to a 'pool' of metals in the material economy; or the harvesting of timber from natural forests). As such, resource extraction essentially adds value to the resources naturally present by supplying them to a point and in a form where they are useful for the economy.

- **Resource dissipation** as the loss of resources from the technosphere in such a way that it is not possible to recycle them back into the technosphere. As an example, we could mention fuel incineration, or the copper used in the chromium-copper-arsenic treatment of woods as highlighted in the work of Ayres et al. (2001, 2003).

There are further concepts that are common to impact assessment of all groups of functional resources, be they biotic or abiotic. Below, we discuss these common concepts and define the generic terms that are used in the further development of the framework. In section 3, we explore specific issues for applying the framework to each of the groups of resources.

2.1 Functionality and existence values

In this paper we deal specifically with the functional values of natural resources, as opposed to their intrinsic or existence values. Most abiotic resources have only functional value to humans, i.e. they are valuable because they enable us to achieve other goals that have intrinsic value, such as human welfare, human health, or existence values of the natural environment. A few resources have intrinsic value to humans; these are mainly unique landscapes and unique archaeological sites. These resources have a distinctly different nature from functional resources and are dealt with separately in section 3.7.

2.2 Consideration of indirect impacts

In some situations, use of natural resources may have an indirect impact on other damage categories with intrinsic value. For example, the use of scarce freshwater may reduce the availability of freshwater for human use and lead to, among other effects, disease. This is independent of the assessment of the impact of freshwater use on the freshwater resource itself, i.e. it is an additional impact pathway, which should be followed in addition to the functional assessment outlined in this paper. In the treatment of the individual resource groups (included in section 3), we highlight where such impact pathways towards intrinsic damage categories may be found.

2.3 Overview of the framework

Fig. 1 shows the relevant flows to and from a product system (i.e. the flows recorded in the LCI result) for any resource. It is a generic description; for individual resource groups, some of the flows may be irrelevant, as described in the section 3 on each resource type. The flows included in this figure are described in detail below.

Input (a) is the amount of the resource used by the system as reported in the LCI. This amount includes only virgin material, since recycled material from the technosphere will not be an inventory item in a terminated product system (out-
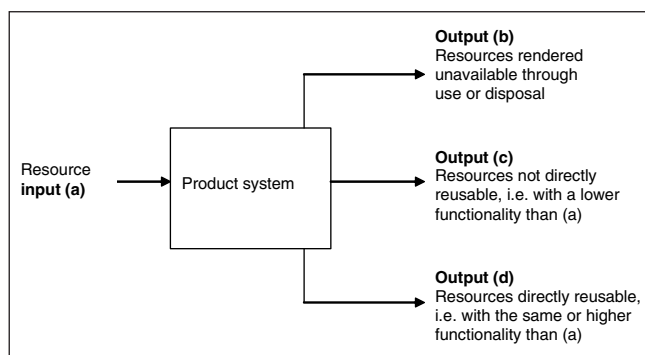
Fig. 1: Flows to and from the product system to be considered for functional resource use

flows of material to recycling will be used as inputs of other processes within the product system, either directly or through system expansion).

Output (b) is the amount of resources made unavailable during use or waste treatment (e.g. dissipated or irreversibly fixed in composites). In this context 'unavailable' is defined to be a concentration or a chemical or physical form that renders the material unavailable for any foreseeable future use by society.

Output (c) is the amount of resource outputs available for reuse, but of a lower quality (functionality) than input (a). The relevant definition of quality and/or functionality depends on the type of resource, as described in section 3 for each resource type.

Output (d) is the amount of resource output that is of the same (or higher) quality (or functionality) as input (a). This does not include material that is recycled within the system (which is already accounted for in the inventory); however, it does include the material which is directly available for recycling, but which is currently not recycled for some reason (e.g. economic or regulatory). An additional quality of output (d) compared to input (a) is a benefit delivered by the system, which can be quantified in terms of the potential savings in concentrating a primary input (a) to the concentration of output (d), which eventually will be realised when output (d) is taken into the economy again.

As the product system is integrated over time, there will be no change in stock within the product system, which implies that:

a = b + c + d

Examples of materials which are dissipated in use (b) are foodstuffs which are consumed, metals which are combined into chemicals and medicines, and coal which is burnt to produce energy.

All such flows are (should be) reported in the LCI result in mass units with a quality/functionality specification (e.g. concentration) relevant for the resource being considered. For impact assessment, what is of interest is the further consequence (impact pathway) of this change of input (a) into outputs (b+c+d). This depends essentially on the future availability of the input (a) and the technologies that will be available to provide this input at the current quality.

2.4 Ultimate quality limit

In Fig. 1 the most significant distinction to be made is that between output (b) and output (c), since we have defined (c) as retaining sufficient functionality to ensure that there is a potential (future) use for the material, while output (b) have no (future) use. We call the limit differentiating output (b) from output (c) the *ultimate quality limit*. We propose that this limit can be determined theoretically based on thermodynamic arguments as the upper bound of the variation in the steady-state background resulting from formation or redeposition (resulting from the dissipative use or disposal of the material), which may be natural or accelerated by human activities. It follows from this definition that the ultimate quality limit will have to be determined individually for each specific resource. A more detailed discussion of the definition of ultimate quality limits for all resource types considered is included in section 3 of this paper. We nevertheless acknowledge that the quantification of these limits may require further research.

2.5 Backup technology

Assuming that the 'virgin' resource input (a) has a decreasing quality/functionality over time, the output streams (c) and (d) will come into service as resources at the point in time when this becomes more economically feasible than utilising input (a). This is essentially a function of the quality/functionality of these output flows (viz., (c) and (d)). According to the definition of ultimate quality limit above, the resources lost (b) will not come into play in this way. However, when the 'virgin' resource input (a) has a decreasing quality/functionality over time, the current loss that output (b) represents will nevertheless require that an alternative technology will have to be used at the time when the quality of input (a) has been reduced to the ultimate limit. Both the technology applied to utilise the output streams (c) and (d) as resources, and the alternative technology applied when reaching the ultimate quality limit are referred to here as the *backup technology* for these output flows.

It follows from this definition that different output qualities may have different backup technologies, and that each backup technology comes into play at a different point in time. For the environmental impact from future backup technologies, we can distinguish four different development scenarios, depicted in **Fig. 2** (*w*, *x*, *y* and *z*).

In Fig. 2 (*w*), the technology providing the current quality of input (a) has an increasing environmental impact over time (the thick line; each step change representing a change in technology[2]). A typical example of this is when high quality mineral ores are depleted and resort must be made to ores of lower quality, requiring more effort (energy) and maybe more land, water and auxiliary chemicals and materials. In this situation, the current societal use of a quantity of input (a) will imply that the resources of this quality will be ex-

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[2] The changes in technology may also be continuous, in which case the line would be sloping. This does not change the argument; it is merely easier to explore the argument with discrete technology jumps.
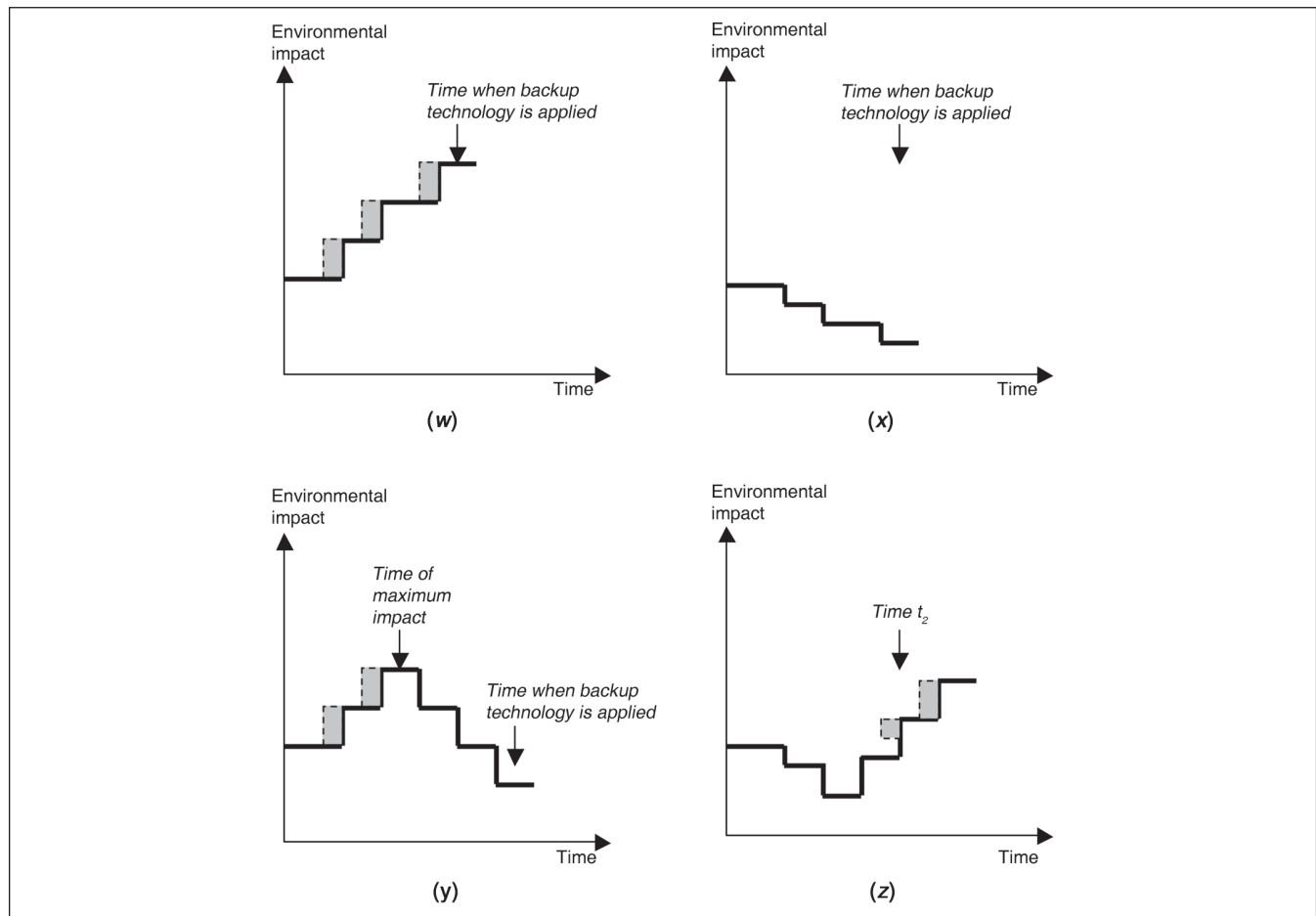
Fig. 2: Environmental impact of the technology to provide the current quality of input (a) as a function of time and the additional impact caused by present losses; (w): technology impacts increase over time; (x): technology impacts decrease over time; (y): technology impacts increase and later decrease; (z): technology impacts decrease and later increase. See text for explanation

hausted at an earlier time than if we had not used this quantity. It will thus be necessary to resort to the lower quality ores and the associated technology at this earlier date. This is represented in the figure by the dotted lines. The hatched areas represent the resulting increase in environmental impact. It can be seen that the hatched areas can be 'stacked' to show that the overall additional environmental impact is equal to the additional environmental impact at the time when the backup technology is applied.

In Fig. 2 (x), the technology to provide the current quality of input (a) has a decreasing environmental impact over time. An example of this may be energy technologies, where future technologies in general are expected to be more environmentally benign than the existing technology suite. In this situation, the future technologies and the timing of their introduction would not be affected by the current use of input (a), and there would thus not be any future additional impacts caused by this current resource use.

In Fig. 2 (y), the technology to provide the current quality of input (a) has first an increase in environmental impact, and then a decrease. An example of this may be fossil fuels, where there may be a depletion of easily accessible reserves leading to an initial increase in extraction efforts, which is eventu-

ally superseded by more efficient alternative energy technologies. Here, the additional future environmental effect of current use of input (a) is still represented by the sum of the hatched areas, in line with the reasoning presented for Fig. 2 (w), also when the backup technology is applied at the later time when the technology is more benign than the current. Thus, the additional environmental impact caused by the current use of input (a) is that of the technology with the largest environmental impact prior to the time that the backup technology is applied.

In Fig. 2 (z), the technology to provide the current quality of input (a) has first a decrease in environmental impact, and then an increase. An example of this could be the more efficient technologies now introduced in minerals extraction, which more than counteracts the current depletion of stocks, but which does not preclude that stocks will eventually be depleted, leading to technologies that are less environmentally benign. When the backup technology is applied before time t_2 (i.e. for high quality output flows) no additional future environmental impact is incurred, but when the backup technology is applied after time t_2 (for low quality outputs and for dissipated material) the additional future impact must be calculated in the same way as for the situation in Fig. 2 (w).

Thus, in the context of the framework developed, the elements that require definition within an LCIA resource depletion model are the:

- ultimate quality limit
- backup technologies

The quality of the input and output flows should be recorded in the LCI.

There has already been significant debate on the quantification of energy consumption by backup technologies for the depletion of metallic resources. The concept was originally suggested by Pedersen Weidema (1991) and Steen and Ryding (1992), with operational contributions from Steen (1999), Müller-Wenk (1999), Goedkoop and Spriensma (1999) and Weidema (2000). At this stage it is not necessarily possible to determine which of these is the best methodology to be adopted for identifying backup technologies. However, what can be stated about the energy requirement for backup technologies is that:

- The *lower limit* for the energy requirement (the least amount of effort), is the difference in the entropies of output (c) and the current input (a); this is the thermodynamic limit which cannot be improved upon within the current understanding of physics[3].
- The *upper limit* for the energy requirement for the backup technology is the energy requirement of existing technology to convert the output (c) to the current input (a); this statement being made with the (robust) assumption that any future technology developments will only improve the efficiency of technologies (i.e. technological efficiency will not decrease in future).

The amount of effort required of the 'backup technology' thus lies within the envelope of energies defined by the upper (existing technologies) and lower (entropic) limits described above. Thus, while it may not be possible to identify the backup technology unambiguously, it is possible to place it within bounds and thus make the general framework operational.

3 Application of Framework to Abiotic and Biotic Resources

Below we discuss the application of the general framework to each of the resource categories identified in this paper, and highlight specific issues for each category. These sections include considerations of the quality/functionality unit for each resource category, an indication of how the ultimate quality limit might be set, and a consideration of backup technologies.

3.1 Metallic minerals

The functionality delivered by metals within the industrial economy is relative to both the concentration of the metal and its form (wire, plate, pipe, etc). As a first assessment however, we look at the functionality of metals as a result of concentration only.

Using copper as an example, copper ores are typically mined at between 0.5 and 1.5% (input (a)) and refined to 99.99% before being used in the production of desired end-products. It is assumed that the effects of mining activities will be captured through other impact categories. Only 1% of copper is used dissipatively (in chemicals and pesticides) (output (b)), a relatively small percentage of copper is alloyed to deliver brass. The majority of copper is used as 99.99% copper in products (Ayres et al. 2001, Ayres et al. 2003). The overall concentration of copper in different products is a function of the amount of copper used in the product. Over and above the 1% of copper placed explicitly in dissipative uses, copper also dissipates *during* use (for example from roof tiles), and copper can be disposed of dissipatively. The environmental effects of this dissipation are all captured as an eco-toxicity effect in LCA.

In attempting to define the ultimate quality limit (or the limit of concentration below which flows are assigned to be of type output (b), the proposal has been made (Steen and Ryding 1992) that this be some multiple of the background concentration for the metal. It will be necessary to define a specific limit for each metal. This limit should take into consideration both the concentration and mineralogy of mined minerals.

Mining of virgin ores (input (a)) will continue to the point that ore grades decrease below that of solid waste deposits (output (c)) at which point input (a) will be replaced by inputs from stockpiled outputs (c). This is already the case in the South African gold industry where mine dumps are routinely re-mined for their gold content. This will be supported in the main by economic considerations (and specifically consideration of supply and demand and resulting pricing structures, which are a function of resource availability) and technological feasibility, than by physical resource depletion.

With respect to metals which are alloyed, it must be recognised that there are thermodynamic contraints on recovering metals in their pure forms from alloys. The most significant case in point here is nickel, more than 80% of nickel produced on a global basis is used in the production of stainless steel (NiDI 2004). Thus it is necessary for the framework developed to be able to engage with metals which are not used in their pure form. However, it must be recognised that the functionality for which alloyed metals are required are the characteristics which they deliver to the alloys for which they are used. At present alloyed metals are extracted to deliver this functionality. As long as the alloys are not used or disposed of dissipatively they report to streams (c) and/or (d) in the proposed framework. The complxity arises when the metals are desired for functionalities other than their alloying functionalities as it may not be possible to recover these metals from their alloy matrices. This potential shift in future metals use is difficult to predict or even visualise, suffice it to say that the framework developed is able to engage with existing metals use profiles.

3.2 Non-metallic minerals

In the past, LCA has paid scant attention to the depletion of non-metallic minerals. Some non-metallic minerals deliver their desired functionality as a result of their shape and form. Thus,

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[3] Note: Here entropy differences are considered, in this context it is not necessary to define a basis for the calculation of absolute entropy requirements; thus the complexity associated with Type 4 methodologies discussed in section 1 does not arise.

if these are broken down in use (for example if marble is shattered when a building is demolished) then the material can no longer deliver the function for which it is exploited.

The depletion of non-metallic minerals is of greater concern than metallic minerals, as metallic minerals can generally be recovered, limited only by consideration of energy inputs, while non-metallic minerals are desired for their form which is often destroyed in use or disposal. For the majority of non-metallic minerals it is not sensible to reconstitute the material properties, which implies that the backup technologies will not be recycling (as for metals) but rather the production of an artificial substitute material (for example terrazzo instead of marble). Exceptions to this rule may occur.

It can be assumed that for the majority of non-metallic minerals, output (d) will not exist since the effort required to deliver a recyclable output (d) will be so high that the output will be recycled directly, in which case it will be included in the inventory.

It should be possible to define the ultimate quality limit as a particle size for each non-metallic mineral smaller than which it is no longer possible to exploit the function of the material. This particle size would need to be defined individually for each non-metallic mineral.

The resources depleted (or the functionality lost) through changing input (a), for example a slab of marble, into output (c), e.g., marble chips from a demolition site, is related to the difference in particle size between the two flows. This assessment would deliver a first order assessment of functionality lost.

Those non-metallic minerals whose functionality results from attributes other than their shape and form can, in the main, be assessed in a similar manner to that used for metallic minerals. These non-metallic minerals are desired for a functionality which is most often dependent on their purity. For some of these minerals attention will also need to be paid to form in the definition of the ultimate quality limit.

3.3 Energy carriers

Energy minerals are easier to discuss when considered as two distinct categories – fossil or carbon based fuels, and nuclear fuels. Including nuclear fuels as energy minerals and not as metallic minerals is a subjective choice, which could be debated at a later date.

Focussing first on fossil fuels, these are generally entirely dissipated in use – output (b) – contributing to global warming with limited potential for recovery. Whether there will be an additional environmental impact from future energy technologies is currently an open question. In general, future energy technologies are expected to be cleaner than present options as we move towards a solar economy. However, there may be an interim reliance on lower grade fossil fuels and nuclear fuels that may temporarily involve additional impacts. These impacts should be included in the impact assessment following the logic described by Fig. 2(y).

While the nuclear fuel minerals are not dissipated as such, their energy content is dissipated in much the same way as for fossil fuels. While this is true for the mineral itself, it is not true for its exergy state. This implies that the backup technology will be identical to that for fossil fuels.

3.4 Water

Water can be found in different input (a) qualities and different output (c + d) qualities. Water is an output of type (c) if it has a lower quality than input (a); and an output of type output (d) if it is of the same or higher quality as the original water input (a). Water can be dissipated in use, e.g. when injected into oil wells or when consumed in chemical reactions.

It is recognised that a significant number of water quality definitions already exist. In the main these qualities are available on a country specific basis. These available water qualities should be used to determine the benefits to the system of supplying output (d), and the backup technologies required for outputs (b) and (c), respectively. It should be noted that water quality can not be defined in terms of a single indicator, water quality is multi-dimensional. Thus the ultimate quality limit for water needs to be defined relative to a vector of water quality characteristics.

The backup technology is thus the technology that will be used to return output (b) or (c) to quality (a) when and where such a supply is required (i.e. in areas of water scarcity). Desalinisation of seawater may be used as the ultimate backup technology in areas of water scarcity, for replacing water quality lost through a system that uses input (a) and has output (b).

Further work has been conducted on the inclusion of water quality as an indicator for water resource use by the LCIA draft author team of the UNEP/SETAC Life Cycle Initiative (Jolliet et al. 2003). The general framework for resource depletion developed in this paper is directly applicable to the outcomes of that work. It should be noted that the work of Jolliet et al. (2003) includes comments on the contribution of water usage to intrinsic damage categories. Unlike minerals, water does deliver functionality that may affect intrinsic indicators significantly.

3.5 Soil

Soil is similar to water in that a number of different soil qualities can be defined (based to a significant extent on its (potential) productivity). Further, soil quality must also be defined according to a vector of qualities.

Soil can be dissipated (output b), which is in some cases included in LCIs as dust or particles. Note should be taken that some soil lost through erosion may be re-deposited on agricultural lands, in which case only the net dissipation should be included in the further impact assessment.

During land use, soil quality may be depleted (output c) or improved (output d). Soil depletion will require the application of backup technologies to provide the same productiv-

ity as for the original soil input (a). Backup technologies may either be soil maintenance activities that bring back the original productivity, and/or alternative means of producing the same products (e.g. on a larger area of lower quality soils) until original soil quality has been restored. In the latter case, temporary reductions in global food output may result, affecting intrinsic damage categories. As is the case with water, soils deliver functionalities that can have significant effects on intrinsic damage indicators.

An ultimate quality limit can be defined, i.e. the limit at which it is unlikely that a depleted soil will be recovered for use. The ultimate backup technology for soils that are made unavailable may be soil-less agriculture (hydroponics and production of single-cell protein).

3.6   Biotic resources

By biotic resources, we mean plants and animals that have a functional value to humans as opposed to an intrinsic or existence value. Thus, we deal here with stocks of wild plants and animals that are harvested for human use, as well as the production of the agri-, silvi- and aqua-culture industries.

Harvesting of biotic resources in excess of their natural surplus can lead to both temporary and permanent reduction in the production capacity. The production capacity of biotic resources may also be affected by other impact pathways than direct harvesting (e.g. by emissions of growth enhancing or limiting substances).

Temporary reductions in production capacity of biotic resources can be dealt with in the same manner as depletion of other functional resources, by applying backup technologies to provide the same productivity as before the change. Backup technologies may either be maintenance activities for the populations in question (such as improving breeding and growth conditions) that bring back the original productivity, and/or alternative means of producing equivalent products (for example, utilising larger areas to provide the same yield or utilising stocks that demand more harvesting efforts) until original productivity has been restored. In the latter case, temporary reductions in global food output may result, affecting intrinsic damage categories. As is the case with soil and water, biotic resources deliver functionalities that can have significant effects on intrinsic damage indicators.

Permanent reduction in the production capacity of biotic resources, i.e. irreversible effects of non-sustainable utilisation, is an impact pathway towards the intrinsic impact indicator 'biodiversity.' Permanent impacts on wild species can be modelled in parallel to other biodiversity impacts, such as those caused by physical impacts of land use (see for example Weidema & Lindeijer 2001). The importance of a permanent impact on domesticated species may depend on the current existence or non-existence of the natural ancestors to the domesticated species, i.e. the degree of irreversibility in the loss. In case of reversibility, the impact may be modelled through the use of backup technologies provided to restore the lost species. In the case of irreversibility, the

loss may be valued as being more severe than the loss of a wild species, since domesticated species are often of special concern to humans, both as species type and for the cultural aspects of domestication. Thus, the loss of domesticated species should be kept as a separate impact category and not summed up with other categories of biodiversity.

3.7   Unique landscapes and archaeological sites

As mentioned previously, unique landscapes and archaeological sites have intrinsic value to humans, rather than functional value. Therefore, they place very different requirements on impact assessment models, which cannot follow the above-described schema for functional resources. The impacts on unique landscapes and unique archaeological sites are fundamentally related to landscape transformation, whether this transformation is one from a natural state into human use, from one human use to another, or a relaxation from human use. Thus, this impact category would be better addressed if it were grouped under the physical impacts of land use. However, for the sake of completeness we consider these resources in this paper.

Precisely because of their uniqueness, the value of unique landscapes and unique archaeological sites cannot be determined in terms of a general indicator, but must be treated on a case-by-case basis. However, an indicator may be developed for disruption of unknown archaeological sites (i.e. possibly but not necessarily unique), since this can be related to increases in ploughing depth, introduction of deep-rooted plants, and other activities that disturb or remove soil layers that were previously undisturbed. Thus, an indicator may be based on the thickness of soil layer disturbed. This indicator should be multiplied by the area, and weighted by a factor determined by archaeologists and historians, expressing the probability of occurrence of archaeological remains in different area types (and soil depths). Predictive models for this purpose are in development (see for example Dalla Bona 1994). The possibility for a meaningful classification of area types depends also on the ability of the life cycle inventory to identify the location of specific activities within such classes.

4   Conclusions and Recommendations

In this paper we have presented a general framework for the assessment of resource depletion associated with any production system. The proposed framework is robust and applicable to all resource categories considered within LCIA; in addition it has been extended to incorporate some resources not traditionally addressed. In developing this framework we have focused on the desired functionality delivered by resources. This has moved our focus from the extraction of desired materials, to their dissipation through use and disposal. We have defined two parameters that need to be defined for each resource being considered, namely the ultimate quality limit and the backup technology. Using these terms, together with and understanding of the functionality desired of the resource, it is possible to quantify the effects

of resource depletion for all the resource categories considered. We have presented a first order assessment of how it is possible to determine values for these parameters for the complete set of biotic and abiotic resources considered within LCA at present. These discussions demonstrate that, in general, resource depletion is unlikely to limit the potential of any production system to continue in the long term. This is not to say that resource depletion as an impact category should necessarily be excluded from LCA, but rather that when included, the focus of this category should be on the dissipation of resources, which represents the only area of possible concern.

In order to implement the general framework presented in this paper, it will be necessary to determine values for:

- Functionality/quality indicator for each resource
- Ultimate quality limit for each resource
- Backup technologies for each resource

The functionality for each resource needs to be recorded in the LCIs. Values determined for ultimate quality limits and backup technologies will be applicable across LCA studies and can therefore be integrated in impact assessment modelling. A significant amount of work already exists which can be used to inform the determination of these parameters, and this information remains to be collated and synthesised before any attempt is made to address gaps in information available.

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